Constraints on the Acceleration of Ultra-High-Energy Cosmic Rays in Accretion-Induced Collapse Pulsars

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ABSTRACT

We have recently proposed that the ultra-high energy cosmic rays (UHECRs) observed above the GZK limit could be mostly protons accelerated in reconnection sites just above the magnetosphere of newborn millisecond pulsars originated by accretion induced collapse (AIC-pulsars). Although the expected rate of AIC sources in our own Galaxy is very small ($\sim 10^{-5}$ yr^{-1}), our estimates have shown that the observed total flux of UHECRs could be obtained from the integrated contribution from AIC-pulsars of the whole distribution of galaxies located within a distance which is unaffected by the GZK cutoff (~ 50 Mpc). We presently examine the potential acceleration mechanisms in the magnetic reconnection site and find that first-order Fermi acceleration cannot provide sufficient efficiency. To prevent synchrotron losses, only very small deflection angles of the UHECRs would be allowed in the strong magnetic fields of the pulsar, which is contrary to the requirements for efficient Fermi acceleration. This leaves the one-shot acceleration via an induced electric field within the reconnection region as the only viable process for UHECR acceleration. We formulate the constraints on both the magnetic field topology and strength in order to accelerate the particles and allow them to freely escape from the system. Under fast reconnection conditions, we find that AIC-pulsars with surface magnetic fields 10^{12} G $< B_\star \lesssim 10^{15}$ G and spin periods 1 ms $\lesssim P_\star < 60$ ms, are able to accelerate particles to energies $\geq 10^{20}$ eV, but the magnetic field just above the Alfvén surface must be predominantly toroidal for the particles to be allowed to escape from the acceleration zone without being deflected. Synchrotron losses bring potentially important constraints on the magnetic field geometry of *any* UHECR accelerators involving compact sources with strong magnetic fields.

Subject headings: **ultra-high energy cosmic rays: theory, acceleration; - pulsars: general; - stars: neutron - stars: white dwarfs - stars: magnetic fields**

1. Introduction

The origin and nature of the observed cosmic ray events with energies beyond 10^{20}eV remains a mystery. Up to now, more than 55 with $E > 4 \times 10^{19}$ eV have been detected (Takeda et al. 1999), and the similarities of their air showers with those of cosmic rays at lower energies suggest that they could be mostly protons (Protheroe 1999), although the possibility that they are heavy nuclei, $\gamma-$rays, neutrinos, or exotic particles cannot be totally ruled out at the present. If these ultra-high energy cosmic rays (UHECRs) are mostly protons, then they should be affected by the expected Greisen-Zatsepin-Kuzmin (GZK) energy cutoff ($\sim 5 \times 10^{19}$ eV for protons), due photo-pion production by interactions with the cosmic microwave background radiation, unless they are originated at distances closer than about 50 Mpc (e.g., Protheroe & Johnson 1995, Medina Tanco, de Gouveia Dal Pino & Horvath 1997). On the other hand, if the they are protons from nearby sources (located within $\sim$ 50 Mpc), then they should be little deflected by the intergalactic and Galactic magnetic fields and point toward their sources (e.g., Stanev 1997, Medina Tanco, de Gouveia Dal Pino & Horvath 1998).

Magnetic confinement of UHECR by the Galaxy is very difficult since the Larmour radius for a proton with energy $E \simeq 10^{21}$ eV is of the order of few 100 kpc, and the present data although statistically modest, also seem to indicate an extragalactic origin for the UHECR events. There is no significant large-scale anisotropy related to the Galactic disk, halo, or the local distribution of galaxies, although some clusters of events seem to point to the supergalactic plane (Takeda et al. 1999).

In an attempt to disentangle the puzzle presented by the detection of these particles with extremely high energies, several source candidates and acceleration mechanisms have been invoked, but all of them have their limitations (see, e.g., Protheroe 1999, Blandford 2000, and Olinto 2000, 2001, for reviews). The proposed models can be separated in two

classes: (i) the so called astrophysical Zevatrons, or $buttom - up$ models, which involve searching for acceleration sites in known astrophysical objects that can reach the required ZeV energies, such as compact sources with high magnetic fields and rotation rates, or powerful shocks; and (ii) the $top - down$ models that involve the decay of high mass relics from the early Universe. Among the Zevatrons, shock acceleration in the radio lobes and jets of powerful radio sources and AGNs may appear as an attractive possibility (e.g., Rachen & Biermann 1993), but the lack of direct correlation of the arrival directions of most of the observed UHECRs events with nearby radio galaxies or AGNs poses some difficulties to these candidates. Among the top-down models, the production of UHECRs by hadronization of quarks and glouns generated during the evaporation of primordial black holes located mainly at an extended Galactic halo has been recently examined as an alternative possibility (Barrau 1999).

Other potential Zevatrons are unipolar inductors, like millisecond pulsars with very strong magnetic fields (B $> 10^{12}$ G), or magnetars. Particles can, in principle, extract the required energies from an induced e.m.f. across the few open field lines of a rapidly rotating magnetar, although a large electric field parallel to the magnetic field can be easily shorted by electron-positron pairs. Alternatively, the particles can be accelerated in reconnection sites of magnetic loops produced, e.g., by Parker instability, on the surface of a magnetar (Medina Tanco, de Gouveia Dal Pino & Horvath 1997), but the accelerated particles will probably lose most of their energy gain by curvature radiation while dragged along by the magnetic dipole field (Sorrell 1987).

To overcome these difficulties imposed by acceleration in regions located close to the surface of a pulsar, in a recent work (de Gouveia Dal Pino & Lazarian 2000, hereafter Paper I), we have speculated that UHECRs could be mostly protons accelerated in magnetic reconnection sites *outside* the magnetosphere of newborn millisecond pulsars produced

by accretion induced collapse (AIC) of a white dwarf (e.g., Woosley & Baron 1992 and references therein). As stressed in Paper I, the accretion flow spins up the star and confines the magnetosphere to a radius R_X where both plasma stress in the accretion disk, and magnetic stress balance (Arons 1993). At this radius, which also defines the inner radius of the accretion disk, the equatorial flow diverts into a funnel inflow along the closed field-lines toward the star, and a centrifugally driven wind outflow (Gosh & Lamb 1978, Arons 1986, Shu et al. 1999). To mediate the geometry of dipole-like field lines of the star with those opened by the wind and those trapped by the funnel inflow emanating from the R_X region, a surface of null poloidal field lines is required. It is labeled as "*helmet streamer*" in Figure 1a. (see also Fig. 1 of Paper I).

Across the null surface, the poloidal field suffers a sharp reversal of direction. According to the Ampère's law, large electric currents must flow out of the plane shown in Figure 1a, along the null surfaces, and in the presence of finite electric resistivity, dissipation of these currents will lead to reconnection of the oppositely directed field lines (e.g., Biskamp 1997, Vishniac & Lazarian 1998). Helmet streamers (or flare loops) are also present in the magnetic field configuration of the solar corona. The magnetic energy released by reconnection in the helmet streamer drives violent outward motions in the surrounding plasma that accelerate copious amounts of solar cosmic rays without producing many photons (Reames 1995). A similar process may take place in the helmet streamer of young born AIC-pulsars.

The particular mechanism of particle acceleration during reconnection events is still unclear in spite of numerous attempts to solve the problem (see LaRosa et al 1996, Litvinenko 1996). Cosmic rays from the Sun confirm that the process is sufficiently efficient in spite of the apparent theoretical difficulties for its explanation. In this situation we attempt to place constraints on the geometry of the magnetic field at the reconnection

sites and identify the most promising processes that can provide UHECR acceleration at AIC-pulsars.

We have argued in Paper I that protons could be accelerated to the ultra high energies in AIC-pulsars by the large induced electric field within the reconnection region (e.g., Haswell, Tajima, & Sakai 1992, Litvinenko 1996). This allowed us to obtain a flux of UHECRs which was consistent with the observations, but the physics of the acceleration process itself was not discussed there. In this paper, we investigate the potential acceleration mechanisms in the reconnection site. We first examine the conditions at which the rate of magnetic reconnection itself can be maximized in the presence of anomalous resistivity (¶2). Then, we show that first-order Fermi acceleration in the reconnection site is possible, but it cannot produce UHECRs because of the synchrotron losses that the particles experience in the strong magnetic fields of the pulsars (¶3). We finally formulate the necessary constraints on the magnetic field geometry in order to enable one-shot acceleration by the induced electric field in the reconnection region, re-evaluate the expected UHECR spectrum and flux (¶4), and conclude with a brief discussion of the implications of our results (¶5).

2.   Anomalous Resisistivity in the Reconnection Region

The commonly referred problem in classical reconnection schemes is that they use to provide too slow reconnection rates. For instance, Sweet-Parker reconnection implies a reconnection rate that is smaller than the Alfvén speed by a factor $R_{eM}^{-1/2}$, where R_{eM} is the magnetic Reynolds number. This factor can be as small as 10^{-10} in the ISM, and makes the reconnection rate extremely slow. Very slow reconnection rates would make the losses too large and the acceleration inefficient. However, there is ample observational evidence that reconnection in Astrophysics takes place at much larger rates which are instead comparable with the Alfvén speed (e.g., Dere 1996). In a recently suggested model of turbulent

reconnection, Lazarian & Vishniac (1999, hereafter LV99; 2000) have appealed to an inevitable wandering of magnetic field lines as the ultimate cause of fast reconnection[3]. The scheme explains naturally flaring and other Astrphysical phenomena, but numerical testing is still required. A competing model based on plasma properties (Bisckamp, Schwarz & Drake, 1997) to stabilize the Petcheck reconnection layer has also been recently put forward. Further research should determine the domains of each particular scheme's applicability.

Presently, let us focus our attention on regions of strong magnetic fields, like those around pulsars. In this case, fast reconnection (with $v_{rec} \sim v_A$) is ensured by anomalous resistivity (see Parker 1979). Following LV99, we can estimate the width of the current sheet for which the resisitivity should be anomalous:

$$\delta = \frac{c\Delta B}{4\pi n Z e u} \tag{1}$$

where $\Delta B \simeq B$ denotes the change of the magnetic field across the reconnection region, n the particle number density, and u the thermal velocity of the ions of charge Ze. At the radius R_X, where the magnetic field corrotates with the pulsar (see Fig. 1a), the particle density has approximately the Goldreich-Julian value (e.g., Goldreich & Julian 1967) $n \simeq B(R_X)\Omega_\star/4\pi Z e c$, which implies

$$\delta \simeq 10^9 \mathrm{cm}\, \Omega_{2.5k}^{-1} u_9^{-1} \tag{2}$$

where u_9 is the thermal velocity in units of 10^9 cm s^{-1}, and $\Omega_{2.5k} = \Omega_\star/2.5 \times 10^3$ s^{-1}, with $\Omega_\star$ being the angular speed at the stellar surface. Although this estimate is somewhat crude, the value of $\delta \simeq 10^9$ cm indicates that the conditions in the pulsar are more than

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[3]Recently Kim and Diamond (2001) noticed that in the problem of reduced dimensionality (less than 3D), the reconnection is slow in spite of the stochastic character of the magnetic field lines. This is consistent with the claim in Lazarian & Vishniac (1999), where the three-dimensionality of the field wandering was required.

appropriate to produce fast reconnection through anomalous resistivity over the entire region since $\delta >> R_X$ (see below).

Therefore, whatever processes are invoked to accelerate the particles, it is realistic to assume that the reconnection velocity that we deal with is an appreciable fraction of the local Alfvén velocity. Besides, as in the conditions we deal with this speed approaches c, the expected acceleration rate can be very large. Any limitations on the efficiency at which acceleration may occur will then come solely from the way by which particles will manage to escape from the strong magnetic fields around the pulsar.

3. Synchrotron Losses

A schematic representation of a reconnection region is shown in Figure 1b. The upper and lower parts of the magnetic flux move towards each other with a velocity v_{rec}. As a result, charged particles in the upper part of the reconnection zone "see" the lower part of the magnetic flux to approach them with a velocity $2v_{rec}$, and an acceleration process analogous to the first-order Fermi acceleration of cosmic rays in magnetized shocks (e.g., Longair 1992) may take place. In fact, it is straightforward to show that, during a round trip between the upper and lower magnetic fluxes, a particle will suffer an average increment of energy

$$\langle\frac{\Delta E}{E}\rangle \simeq \frac{8}{3}\frac{v_{rec}}{c},$$
(3)

so that after a number of crossings the particles could in principle reach the required ultra-high energies. However, in the very strong magnetic fields present in the young pulsar, the particle energy losses due to synchrotron radiation can be rather substantial. Let us evaluate them.

A well known formula for the power radiated by a moving charged particle is (e.g.,

Jackson 1981)

$$P_r = \frac{2}{3} \frac{e^2}{m^2 c^3} \left[\left(\frac{d\mathbf{p}}{d\tau} \right)^2 - \frac{1}{c} \left(\frac{dE}{d\tau} \right)^2 \right] \tag{4}$$

where $d\tau = dt/\gamma$ is the proper time element. A usual assumption in the derivation of the synchrotron losses formulae is that $c\, d\mathbf{p}/d\tau \gg dE/d\tau$, which means that the particle momentum, $\mathbf{p}$, changes rapidly in direction without relevant changes in E during a particle revolution around the magnetic field line. In this case, after simple algebra one can easily get

$$\frac{\delta E}{E} \approx 3.7 \times 10^{12} \, \delta\varphi B_{13} E_{20}^2 \sin\theta \tag{5}$$

where δE is the amount of energy lost by the particle of energy $E_{20} = E/10^{20} eV$, when deflected by an angle $\delta\varphi$ in a magnetic field $B_{13} = B/10^{13} G$, and θ is the pitch angle between the magnetic field and the particle velocity.

It is clear from Eq.(4), however, that for the regime that we are interested, i.e., in the case of UHECR acceleration, the energy losses per revolution period may be very substantial. In this case, the classical synchrotron loss formulae should be modified. Rewriting Eq.(4) in the form

$$\frac{P_r}{2e^2/3m^2 c^3} = \left(\frac{d\mathbf{p}}{d\tau} \right)^2 - \frac{1}{c^2} \left(\frac{dE}{d\tau} \right)^2 \tag{6}$$

and taking into account that $P_r = dE/dt = dE/d\tau$ is a Lorentz invariant we get a quadratic equation for P_r:

$$P_r/D = (\gamma \omega_B E/c)^2 - 1/c^2 P_r^2, \tag{7}$$

where $D = 2e^2/3m^2 c^3$, and $\omega_B = eB \sin\theta/mc\gamma$ is the Larmor frequency of the particle. The solution of this equation is

$$P_r = \frac{c^2[-1 + (1 + \Delta)^{1/2}]}{2D} \tag{8}$$

where $\Delta = (4/c^2)(D(\gamma \omega_B E/c)^2$. In the case of $\Delta \gg 1$, it reduces to

$$P_r \simeq \gamma \omega_B E \tag{9}$$

which means that for $\Delta \gg 1$, the energy loss per deflection $\delta\varphi$ will be $\delta E \simeq P_r \delta\varphi/\omega_B$, or

$$\frac{\delta E}{E} \approx 1.04 \times 10^{11} \delta\varphi E_{20} \sin\theta, \tag{10}$$

which is independent of the magnetic field intensity. Comparing Eqs. (10) and (5), we see that the corrected synchrotron losses for UHE particles decreases by only an order of magnitude relative to the original evaluation. Therefore, in the UHE particle regime, the synchrotron losses in strong magnetic fields are so large, even for very small deflection angles, that they exclude any possibility for particle acceleration via reflecting particles back and forth within the reconnection zone, as required in first (or second) order Fermi acceleration processes. Fermi acceleration would be possible for UHECRs only if the magnetic fields in the system were relatively weak. As indicated by Eq. (5), for an E_{20} particle, B must be $\lesssim 1$ G in order to cause no relevant energy losses for finite particle deflection angles. Since in the AIC-pulsars, very strong magnetic fields are present and actually provide the energy reservoir for particle acceleration, we conclude that Fermi processes are not suitable in this case. We show below instead, that direct acceleration by the induced electric field in the reconnection zone is the only viable mechanism.

4. Model for One-Shot UHECR Acceleration in the Reconnection Region

In Paper I, we have argued that the protons could be accelerated by a large induced electric field within the reconnection region in the helmet streamer (Haswell et al. 1992, Litvinenko 1996), but now we find that an additional constraint should be applied to the magnetic field geometry, namely, that the accelerated UHECRs should escape without experiencing any significant deflection, otherwise their gained energy would be lost by synchrotron effects in the strong poloidal fields.

In the idealized two-dimensional field topology suggested in Paper I (see Fig. 1a), the

reconnection site was a simple straight sheet along which the particles were accelerated by an electric field coming out of the plane shown in Fig. 1a, so that the particles could escape freely from the system on the normal direction to the plane of Fig. 1a. However, in a more realistic three-dimensional geometry, the reconnection region of Fig. 1a actually describes a cone around the rotation axis of the star, so that the accelerated particles escaping perpendicularly out of the plane of Fig. 1a will be eventually strongly deflected by poloidal field lines in their way out of the system, thus loosing most of their energy (Eqs. 5 and 10).

On the other hand, it is well known from magnetized-winds theory (e.g., Spruit 1996) that beyond the Alfvén surface (that is the surface at which the wind flow emerging from the disk/star system reaches the Alfvén velocity, v_A), the inertia of the gas causes it to lag behind the rotation of the field line, so that the poloidal lines $(\vec{B}_p)$ get wound up thus developing a toroidal component $(\vec{B}_\phi)$ (see a schematic representation of the field line winding process in Figure 2a). In the extreme relativistic limit, the inertial forces in the flow are so high near the Alfvén surface that they bend the poloidal lines into nearly horizontal shape, and the field becomes preferentially spiral, i.e. $B_\phi \gg B_p$ (e.g., Camezind 1987). In this case, as the accelerating electric field, which is perpendicular to the annihilating magnetic field lines, is mostly poloidal $(\vec{\epsilon}_p)$ (see Figure 2b), the particles will be accelerated (and allowed to escape) along the poloidal direction without being deflected by the field lines, therefore, without suffering substantial synchrotron losses.

Following Paper I, we adopt Shu et al. (1999) field geometry of magnetized stars accreting matter from a disk (Fig. 1a), but take into account the formation of a toroidal magnetic field above the Alfvén surface (Fig. 2a).

For a Keplerian disk, the inner disk edge R_X rotates at an angular speed $(GM_\star/R_X^3)^{1/2}$, and equilibrium between gravity and centrifugal force at R_X will lead to co-rotation of the star with the inner disk edge, i.e., $R_X = (GM_\star/\Omega_\star^2)^{1/3}$, which for typical millisecond pulsars

with rotation periods $P_\star = 2\pi/\Omega_\star \simeq 1.5 - 10$ ms, mass $M_\star \simeq 1$ $M_\odot$, and radius $R_\star = 10^6$ cm, gives $R_X \simeq (2 - 7) \times 10^6$ cm R_6, where $R_6 = R_\star/10^6$ cm. The magnetic field intensity in the R_X region is given by (Arons 93, Paper I)

$$B_X \simeq B_{dipole}(R_X) \left(\frac{R_X}{\Delta R_X}\right)^{1/2} \tag{11}$$

where, ΔR_X is the width of the reconnection zone, $B_{dipole}(R_X) = B_\star (R_\star/R_X)^3$ is the magnetic field that would be present in the absence of the shielding disk, and $B_\star$ is the magnetic field at the surface of the star.

In a reconnection event, an electric field arises inductively along the poloidal direction because of plasma flow across the $\vec{B}$ lines. The condition that particles of charge Ze can be accelerated to energies E by an electric voltage drop, V, is given by $E = ZeV = ZeB_\phi \xi L_X$, where $\xi = v_{rec}/v_A \simeq v_{rec}/c$ is the reconnection efficiency factor, and L_x is the length of the reconnection region (see Fig 2b). For fast reconnection, $\Delta R_X/R_X \lesssim 1$ [4], and $L_X/\Delta R_X \approx v_A/\xi v_A \approx \xi^{-1}$ (e.g., LV99). This results $E \approx Ze\Delta R_X B_\phi$, or

$$\frac{E}{R_X B_\phi Ze} \approx \frac{\Delta R_X}{R_X} \lesssim 1 \tag{12}$$

Assuming that B_ϕ is of the order of B_X we can get a limit on B_ϕ using Eq. (12), and substituting $R_X = (GM)^{1/3}/\Omega^{2/3}$ for the corrotation radius, namely

$$B_\phi \gtrsim \frac{E}{R_X Ze} \approx \frac{E\Omega^{2/3}}{(GM)^{1/3}Ze}. \tag{13}$$

Using Eq. (11), it is easy to obtain

$$B_{13} \gtrsim 0.8 \times E_{20}Z^{-1}\Omega_{2.5k}^{-4/3} \tag{14}$$

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[4]This condition on ΔR_X, which is naturally satisfied if the reconnection is fast (or the resistivity is anomalous; see ¶2), further ensures that the thickness of the neutral reconnection zone is large enough to allow the particles to move freely in the poloidal direction without being deflected by the field lines (B_ϕ) while escaping from the system.

where we have assumed $M_\star = 1 M_\odot$, $R_\star = R_6$, $E_{20} = E/10^{20}$ eV, $\Omega_{2.5k} = \Omega_\star / 2.5 \times 10^3$ s^{-1}, and $B_{13} = B_\star / 10^{13}$ G. We note that a similar condition was derived in Paper I, but from a different requirement, i.e., that ΔR_X should be larger than about twice the particles Larmour radius.

Eq. (14) (see also Fig. 2 of Paper I) indicates that stellar magnetic fields 10^{12} G $< B_\star \lesssim 10^{15}$ G and angular speeds 4×10^3 s$^{-1} \gtrsim \Omega_\star > 10^2$ s^{-1}, which correspond to spin periods 1 ms $\lesssim P_\star < 60$ ms, are able to accelerate particles to energies $E_{20} \gtrsim 1$. Slower pulsars with angular frequencies $\Omega_\star \lesssim 10^2$ s^{-1} require too large surface magnetic fields ($B_\star > 10^{15}$ G) to efficiently accelerate the particles. The values above are perfectly compatible with the parameters of young pulsars and Eq. (14) is thus a good representation of the typical conditions required for particle acceleration in reconnection zones of AIC-pulsars through one-shot process.

A newborn millisecond pulsar spins down due to magnetic dipole radiation in a time scale given by $\tau_\star = \Omega_\star / \dot{\Omega}_\star \simeq \left(\frac{I c^3}{B_\star^2 R_\star^6 \Omega_\star^2} \right)$, which for a moment of inertia $I = 10^{45}$ g cm^2 gives $\tau_\star \simeq 4.3 \times 10^7$ s $B_{13}^{-2} \Omega_{2.5k}^{-2}$. We have shown in Paper I that the condition that the magnetosphere and the disk stresses are in equilibrium at the inner disk edge results a disk mass accretion rate

$$\dot{M}_D \simeq 3 \times 10^{-8} M_\odot \text{s}^{-1} \, \alpha_2^{-2} \, B_{13}^2 \, \Omega_{2.5k}^{7/3} \tag{15}$$

where $1 \gtrsim \alpha_2 > 0.5$ measures the amount of magnetic dipole flux that has been pushed by the disk accretion flow to the inner edge of the disk (Gosh & Lamb 1978, Shu et al. 1994). $\dot{M}_D$ is obviously much larger than the Eddington accretion rate, $\dot{M}_{Edd} \simeq 7.0 \times 10^{-17} M_\odot$ s$^{-1}(M_\star / M_\odot)$, but this supercritical accretion will last for a time τ_D, which is only a small fraction (f_D) of $\tau_\star$ (Paper I). Considering that advection dominated inflow-outflow solutions involving supercritical accretion onto neutron stars predict a total mass deposition on the star $M \sim$ few $0.01 M_\odot$ (e.g., Brown et al. 1999), we have found that $\tau_D \simeq M/\dot{M}_D \simeq 1.3 \times 10^6$

s, or $f_D = \tau_D/\tau_\star \simeq 0.03$ (Paper I), which implies that the most violent reconnection events can live at least for several days. As the acceleration of UHECRs in the reconnection zone will occur during the supercritical accretion event, the spectrum evolution of the accelerated UHECRs will be determined by $\tau_D = f_D \tau_\star$ (see below).

The rate of magnetic energy that can be extracted from the reconnection region is $\dot{W}_B \simeq (B_X^2/8\pi)\,\xi v_A\,(4\pi R_X\,L_X)$, where $v_A \sim c$. Substituting the previous relations into this equation, one finds

$$\dot{W}_B \lesssim 2.6 \times 10^{46} \text{ergs}^{-1}\,\xi\,B_{13}^2\,\Omega_{2.5k}^{8/3}. \tag{16}$$

According to our model assumptions, in a reconnection event an electric field arises inductively and once a particle decouples from the injected fluid, it will be ballistically accelerated by this field. The UHECR flux emerging from the reconnection site can then be estimated as

$$\dot{N} \simeq \frac{\dot{W}_B}{E} < 1.6 \times 10^{38}\,\text{s}^{-1}\,B_{13}^2\,\Omega_{2.5k}^{8/3}\,E_{20}^{-1} \tag{17}$$

for particles with energy $E \gtrsim 10^{20}$ eV, and the particle spectrum $N(E)$ is obtained from $\dot{N} = N(E)\frac{dE}{dt} \simeq N(E)\frac{dE}{d\Omega_\star}\dot{\Omega}_\star/f_D$, or

$$N(E) \lesssim 1.6 \times 10^{33}\,\text{GeV}^{-1}\,Z^{-1/2}\,B_{13}^{-1/2}\,E_{20}^{-3/2} \tag{18}$$

where Eq. (13) has given $d\Omega_\star/dE \simeq 1.2 \times 10^{-5}\text{erg}^{-1}\text{s}^{-1}\,Z^{-3/4}\,E_{20}^{-1/4}\,B_{13}^{-3/4}$ (with the signal made equal in Eq. 13). Eq. (18) above is again similar to the one obtained in Paper I, and predicts that $N(E) \propto E^{-3/2} = E^{-1.5}$, which is a flat spectrum in good agreement with observations (e.g., Olinto 2000).

As the total number of sources formed via AICs in our Galaxy is limited by nucleosynthesis constraints to a very small rate $\tau_{AIC}^{-1} \simeq 10^{-5}$ yr^{-1} (Fryer et al. 1999), we find that the probability of having UHECR events produced solely in the Galaxy is very small (Paper I). However, we can evaluate the integrated contribution due to AICs from all

the galaxies located within a volume which is not affected by the GZK effect, i.e., within a radius $R_{50} = R_G/50$ Mpc. Assuming that each galaxy has essentially the same rate of AICs as our own Galaxy and taking the standard galaxy distribution $n_G \simeq 0.01\,e^{\pm0.4}\,h^3$ Mpc^{-3} (Peebles 1993) (with the Hubble parameter defined as $H_o = h\,100$ km s^{-1} Mpc^{-1}), the resulting flux at $E_{20} \geq 1$ is $F(E) \simeq N(E)\,n_G\,\tau_{AIC}{}^{-1}\,R_G$ (Paper I), which gives

$$F(E) \lesssim 3.1 \times 10^{-29}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\,Z^{-1/2}\,B_{13}^{-1/2}\,E_{20}^{-3/2}\,\tau_{AIC,5}{}^{-1}\,n_{0.01}\,R_{50} \qquad (19)$$

where $\tau_{AIC,5}{}^{-1} = \tau_{AIC}{}^{-1}/10^{-5}$ yr^{-1}, and $n_{0.01} = n_G/0.01$ h^3 Mpc^{-3}. Observed data by the AGASA experiment (Takeda et al. 1999) gives a flux at $E = 10^{20}$ eV of $F(E) \simeq 4 \times 10^{-30}$ Gev^{-1} cm^{-2} s^{-1}, so that the efficiency of converting magnetic energy into UHECR should be $F(E)_{obs}/F(E)/ \simeq \xi' \gtrsim 0.1$ in order to reproduce such a signal.

5. Conclusions and Discussion

In this work, we have studied the processes that could accelerate protons in the reconnection sites just above the magnetosphere of very young millisecond pulsars originated by accretion-induced collapse. Our calculation of the synchrotron losses have testified that any tangible deflection of UHECR in a strong magnetic field results in unrecoverable energy losses. Although this does not prevent the UHECRs to be deflected by weak magnetic fields, like, e.g., the Galactic magnetic field, it makes it essential that the propagation of the UHECRs in the strong magnetic fields of the pulsar be straight. This finding not only imposes limits on the geometry of the reconnecting magnetic field flux in our model, but also brings potentially important constraints on the magnetic field geometry of any accelerating models involving compact sources with strong magnetic fields, like for instance, the pulsar wind model proposed by Blasi, Epstein, & Olinto (2000) to generate UHECRs.

Although the back and forth bouncing of protons within the reconnection region in a

Fermi-like mechanism would entail prohibitive energy losses in the case of UHECRs, the process may be still important for Solar physics, where proton acceleration happens within flares.

On the other hand, our model allows one-shot acceleration of the particles by the electric field created in the reconnection region, but the magnetic field just above the Alfvén surface must be predominantly toroidal for the particles to be allowed to escape freely along the poloidal direction in the acceleration zone without being deflected by the magnetic field lines. Under fast reconnection conditions, we find that AIC-pulsars with surface magnetic fields 10^{12} G $< B_\star \lesssim 10^{15}$ G and spin periods 1 ms $\lesssim P_\star < 60$ ms, are able to accelerate particles to energies $\geq 10^{20}$ eV. These limits can be summarized by the condition $B_\star \gtrsim 10^{13}$ G $(P_\star/2.5 \text{ ms})^{4/3}$ which is valid for fiducial stellar and accretion disk/reconnection parameters. The produced particle spectrum is very flat, as required by the data, and the total flux is given by the integrated contribution from AIC-pulsars of the whole distribution of galaxies within the local universe. However, the efficiency factor for converting magnetic energy in the reconnection to acceleration of the UHECRs needs to be $\xi\prime \gtrsim 0.1$ in order to reproduce the observed flux. These results predict, therefore, an extragalactic origin of the UHECRs, in agreement with the present observations, but as data collection improves, we should expect some sign of correlation with the local distribution of galaxies.

In Paper I, we have formulated some constraints on the size of the acceleration zone due to energy losses by pion and and $e^\pm$ pair production off interactions with an (*overestimated*) population of photons from the radiation field produced by the accretion disk. The same constraints could, in principle, be applied also in the present analysis. Although they do not seem to be important enough to prevent UHECR production, we should note that, as in Paper I, the lack of a theory that can precisely determine the amount of photons effectively

reaching the reconnection zone well beyond the disk has made the estimate above very uncertain. In the future, a self-consistent calculation of the evolution of the star/disk system during the supercritical phase, involving advected-dominated inflow-outflow solutions, is required.

Finally, we should note that although we have essentially discussed the acceleration of protons in the AICs, Eqs. (14), (18) and (19) indicate that the proposed mechanism could be, in principle, also applicable to heavier nuclei (e.g., Fe, for which $Z = 26$). However, since most of the UHECR events from AICs must come from extragalactic sources, it would be more difficult to propagate the nuclei heavier than the protons, because of the additional photonuclear disintegration they suffer (Elbert & Sommers 1995).

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Figure Caption

Figure 1. a) Schematic drawing of the magnetic field geometry and the gas accretion flow in the inner disk edge at R_X. UHECRs are accelerated in the magnetic reconnection site at the helmet streamer (see text). The figure also indicates that coronal winds from the star and the disk help the magnetocentrifugally driven wind at R_X to open the field lines around the helmet streamer (extracted from Paper I); b) Schematic representation of a reconnection region.

Figure 2. a) Development of a toroidal field, B_ϕ, from the winding up of a poloidal line, (B_p), above the Alfvén surface. With each rotation of the line, a loop of field is added to the flow at the Alfvén surface; b) Schematic representation of the reconnection region just above the Alfvén surface.

Helmet Streamer

Coronal
Wind

Helmet
Dome

Funnel Flow

Wind

Reconnection
Ring

Dipole
Field

X-Region

Accretion Disk